

Accepted for publication in the Astrophysical Journal Letters

Uncovering Spiral Structure in Flocculent Galaxies

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ABSTRACT

We present K' ($2.1\mu\text{m}$) observations of four nearby flocculent spirals, which clearly show low-level spiral structure and suggest that kiloparsec-scale spiral structure is more prevalent in flocculent spirals than previously supposed. In particular, the prototypical flocculent spiral NGC 5055 is shown to have regular, two-arm spiral structure to a radius of 4 kpc in the near infrared, with an arm-interarm contrast of 1.3. The spiral structure in all four galaxies is weaker than that in grand design galaxies. Taken in unbarred galaxies with no large, nearby companions, these data are consistent with the modal theory of spiral density waves, which maintains that density waves are intrinsic to the disk. As an alternative, mechanisms for driving spiral structure with non-axisymmetric perturbers are also discussed. These observations highlight the importance of near infrared imaging for exploring the range of physical environments in which large-scale dynamical processes, such as density waves, are important.

Subject headings: galaxies:structure, infrared:galaxies,
galaxies:individual(NGC 2403, NGC 3521, NGC 4414, NGC 5055)

1. Introduction

Flocculent galaxies are most noted for what they lack: large-scale, continuous spiral structure, such as that identified in the grand design spirals M51 and M81. This fundamental

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difference, generally credited to the absence of spiral density waves, makes flocculent galaxies an important class of objects in the study of galactic structure. Consequently, much theoretical and observational work has focused on the physical conditions which affect structure formation in flocculent galaxies. If flocculent spirals have no active spiral density waves in their stellar disks (e.g., Elmegreen & Elmegreen 1984, 1985), star formation is left to occur stochastically (e.g., Gerola & Seiden 1978), thereby forming only localized structures. This assertion has been supported by numerical simulations, which show that model galaxies lacking density wave modes form only small- and intermediate-scale structures (e.g., Elmegreen & Thomasson 1993, Roberts 1993).

This theoretical picture is largely based on observations at optical wavelengths; however, studies of the distribution of dust in galaxies suggest that extinction significantly affects the observed structure at wavelengths as long as $0.8\mu\text{m}$ (I band, see e.g. Rix & Rieke 1993). In addition, optical bands are dominated by emission from recent star formation, which does not necessarily trace the underlying stellar potential. With a significant contribution from old stars (Rix 1993) and as much as an order of magnitude less extinction than at optical bands, near infrared (NIR) imaging of galaxies can provide significant new constraints on models of spiral structure. Indeed, variations in spiral structure between optical and near infrared images of grand design spirals have recently been observed (e.g., Rix & Rieke 1993, Block et al. 1994). However, weakly structured disk galaxies are just beginning to be examined in detail at NIR wavelengths (e.g., M33, Regan & Vogel 1994, hereafter RV94).

We present K' CCD imaging of four nearby flocculent galaxies: NGC 2403, NGC 3521, NGC 4414, NGC 5055. These images show spiral structure on kiloparsec scales, enlarging the sample of galaxies in which regular, spiral structure is detected. Future papers will better define the physical significance of the spiral structure reported here, through comparison with the distribution of gas (molecular + atomic) and recent, massive star formation. In §2 the K' observations and data reduction are described; in §3 the method for highlighting nonaxisymmetric structures by subtracting model bulge and disk components is explained; in §4 the observed spiral structure is described; and in §5 possible origins of spiral structure in flocculent galaxies are discussed.

2. Observations and Data Reduction Techniques

Infrared images in the K' ($2.1\mu\text{m}$) broadband filter (Wainscoat & Cowie 1992) were obtained using the Cryogenic Optical Bench (COB) on the 1.3m telescope of the Kitt Peak National Observatory during 1-5 March 1994. COB uses a 256×256 InSb detector, which

at the time of the observations had $0.94''$ pixels on the 1.3m and a $4'$ field of view. The effective resolution was $2.0''$. The K' data were taken as 20-second exposures and coadded before readout for an exposure time of 120 seconds. Exposures were taken in dithered pairs, followed by a pair of dithered sky frames taken 15-20 arcminutes away from the galaxy center. The galaxy center was then moved successively around the array, in order to produce an $8' \times 8'$ or (in the case of NGC 2403) $12' \times 12'$ mosaiced image. The total exposure time per galaxy was approximately 50 minutes.

Infrared standard stars (Elias et al. 1982; Casali & Hawarden 1992) were observed over a range of airmasses to calibrate the infrared images and derive extinction coefficients. A single flat field was created each night by median filtering all dark-subtracted sky exposures. Individual sky frames were made for each pair of object frames by median filtering the sky frames taken immediately before and after the object frames. For each object frame, the composite sky frame was subtracted, a flat field correction was applied, and a correction for extinction was made. The individual dithered object frames were registered using stars found in the overlap regions from frame to frame, and a χ^2 minimization technique (Regan and Gruendl 1995) was used to create the final mosaic. A correction for the zero point of each mosaic image was made by observing a series of overlapping fields which extended sufficiently far from the galaxy to be free of emission. Astrometry was performed using field stars from the Hubble Guide Star Catalog.

3. Bulge and Disk Decomposition

The resulting K' mosaic images (Figure 1) show the predominantly axisymmetric light distribution expected in flocculent galaxies. However, at low levels non-axisymmetric structure is detectable, extending to $0.2\text{-}0.4 R_{25}$. To better characterize the structures seen in K' emission, modeling and subtraction of axisymmetric components were undertaken. The process is similar to the analysis completed for M33 by RV94: a radial profile constructed by measuring the brightness in concentric annuli is fit simultaneously with two model components, a spherical or flattened de Vaucouleurs $r^{1/4}$ bulge and an exponential disk. The best fit models are then subtracted from the mosaic images. To minimize the contribution from a bright nuclear component (three of the sample galaxies are potential LINERS, Heckman 1980, Keel 1983), the inner 4 pixels ($3.8''$) were excluded from the fit. To minimize the contribution of spiral arms, the radial profile was constructed from the 25th percentile of the brightness distribution in each annulus.

This simple method of disk-bulge decomposition is used only to remove a smooth, axisymmetric luminosity component; a more detailed model should be used in order to

accurately characterize the related mass distribution. The flattened $r^{1/4}$ bulge model inherently assumes an oblate bulge with the same apparent axial ratio as the disk, the value of which was determined from the ellipticity of isophotes within the inner $50''$. Models with spherical and flattened $r^{1/4}$ bulges cannot be distinguished by χ^2 using only a radial profile, but subtraction of a spherical model from K' images of all sample galaxies except NGC 2403 showed large negative residuals along the minor axis, suggesting a non-spherical bulge. Finally, while radial profiles cannot distinguish between spiral arms and other deviations of the light distribution from that of the chosen models, it is not possible to create non-axisymmetric structure in the residual images by subtracting purely axisymmetric models. After subtraction of axisymmetric models, the residuals in all galaxies are less than 0.2 magnitudes near the “arm” structures, indicating that the subtraction of model components is sufficient to characterize low-level spiral structure, which is the focus of this Letter.

The inclination, bulge effective radius, and disk scale length for each galaxy are shown in Table 1. To indicate the quality of the fits, the radial profiles of NGC 4414 and NGC 5055 are compared with the model fits in Figure 2. The radial profile of NGC 2403 shows little emission in excess of an exponential disk, and thus the disk was fit first and the bulge fit to the remaining structure in the profile. In NGC 4414, the small angular size of the galaxy allowed few radial points across the bulge, leading to larger uncertainties in the bulge fit. In the radial profile of NGC 5055, the effects of the approximation of a simple, two-component model are seen: the bulge and disk components have comparable brightness contributions at most radii covered by the profile (Figure 2b). The radial profile of NGC 5055 has a contribution from a strong ring enhancement at $r \sim 40''$ (see §4.1), which encourages a fit of a stronger central component. Disk and bulge models were subtracted from the original K' images to produce the residual images shown in Figure 3. The relatively uncertain bulge contribution in NGC 2403 can be seen in the slight oversubtraction of the inner disk (Figure 3a). Small bar-like residuals in the central $\sim 15''$ are due to uncertainties in the axial ratio of the bulge for these simple models. There is no evidence for strong, kiloparsec-scale bars in the NIR.

4. Spiral structure in flocculent galaxies

The distribution of the residual emission presented in Figure 3 suggests the presence of two components in the NIR spiral structure. The distribution of small-scale, bright features correlates well with the distributions of HII regions detected in $H\alpha$ imaging (Thornley et al. 1996a, in prep.), suggesting a contribution from a younger population, such as K

supergiants (e.g. Rix & Rieke 1993, RV94). However, the presence of a broader, smooth component of emission in the residual maps affirms the higher sensitivity of NIR emission to the smoother distribution of the old stellar population. In the following sections, we describe the structure seen in the residual images.

4.1. Individual Galaxies

NGC 5055. The Sbc galaxy NGC 5055 ($d=7.2$ Mpc) is one of the prototypes for an Arm Class 3 flocculent galaxy (Elmegreen & Elmegreen 1987), but it shows clearly a symmetric, two-arm spiral structure in the NIR (Figure 3d). Each arm extends over 150° in azimuth to a radius of $\sim 2.0'$ (4 kpc, $0.3 R_{25}$) before decreasing in brightness. A ring of excess K' emission at a radius of $40''$ is coincident with a slight enhancement of HII regions seen in $H\alpha$ images (Thornley et al. 1996, in prep.). The bulge axial ratio indicated by inner isophotes is 0.67, while the axial ratio of the disk at larger radii is 0.57, suggesting that the bulge is triaxial.

NGC 2403. NGC 2403 is a nearby (3.2 Mpc) Scd galaxy with similar global properties to the Local Group spiral M33. The NIR residual structure in NGC 2403 is relatively uncertain due to its low surface brightness and minimal bulge, but a two-arm spiral structure is marginally detected (see Table 2), extending over as much as 180° in azimuth to a radius of ~ 2 kpc ($0.2 R_{25}$). The stronger, outer ridges of the spiral structure are also consistent with enhanced star formation at the radius at which the gas surface density in the disk becomes supercritical for star formation (Thornley & Wilson 1995).

NGC 3521. The residual map of the Sbc galaxy NGC 3521 ($d=7.2$ Mpc) shows a tightly wound two-arm pattern (Figure 3b). The eastern arm is long and continuous, extending over 180° in azimuth to 3.5 kpc ($0.3 R_{25}$), while the western arm appears to split in two, leaving a continuous spiral arm over $\sim 130^\circ$ of azimuth to a radius of 2.4 kpc. K' emission from the central region is extremely strong, and is offset from the centroid of the disk by $\sim 2''$ to the west.

NGC 4414. The high gas surface density Scd galaxy NGC 4414 (Braine et al. 1993) is 2.5 times more distant than NGC 3521 (Pierce 1994), and remains the most flocculent of the sample in K' emission. Comparison with $H\alpha$ imaging suggests that much of the residual K' emission in the inner disk (Figure 3c) can be traced to the distribution of HII regions in NGC 4414; for example, bright star forming regions to the northwest and southeast of the nucleus likely contribute to an apparent NIR ring/arm structure of radius $20''$ (2 kpc). Outer “arm” segments to the north and south extend to a radius of $\sim 40''$ ($0.4 R_{25}$), and are

continuous over $\sim 60^\circ$ in azimuth. While these outer structures are similar in linear scale to the arm structures seen in NGC 3521 and NGC 5055, they do not appear to contribute to a regular two-arm spiral pattern.

4.2. NIR Arm-Interarm Contrasts

To compare the stellar density enhancement along the arms with those of grand design spirals, we have measured the arm-interarm contrast in each galaxy, using the arms defined by the residual images. In NGC 5055 this was accomplished using two methods. In the first method, ten regions along each arm were matched with two interarm positions at the same galactocentric radius in the original image. In the second method, the ten selected arm regions were compared with the axisymmetric model (disk + bulge) at the same position. For both methods, the median brightness was measured in a 9×9 pixel region around each position, and the arm-interarm contrast, R , is given by the ratio of the arm to non-arm (interarm or axisymmetric model) brightness. The median is used to minimize the effects of localized enhancements of K' emission due to a younger population of K supergiants. Due to more tightly wound spiral arms or bright foreground stars seen in the K' images, the first method is only feasible in NGC 5055. As it is model-independent, this method is most desirable, but by using both methods in NGC 5055 we confirm that the results are the same to within the uncertainties (see Table 2). The NIR arm-interarm contrasts reported here (Table 2) range from 1.1-1.4. Though the methods for measuring the relative overdensity of the spiral arms are heterogeneous, galaxies which exhibit clear grand design structure (e.g., M51, Rix 1993; M83, Adamson et al. 1987; and NGC 7309 and IC 2627, Rix & Zaritsky 1995) have similarly measured NIR arm-interarm contrasts of ~ 1.5 -3.0, suggesting that flocculent spirals have lower stellar density enhancements than grand design spirals.

5. The Origin of Low-Amplitude Spiral Structure

The images presented in Figure 3 demonstrate the presence of kiloparsec scale spiral structure in nearby flocculent galaxies. While these data do not rule out the existence of truly flocculent galaxies, they suggest that spiral density enhancements may be present in many more (see also NGC 1309 and NGC 1376, Rix & Zaritsky 1995). As the detected arm structure extends past the turnover radius of the rotation curve in NGC 3521 and NGC 5055 (Casertano & van Gorkom 1991, Kent 1987), it is unlikely that the arm structures in these galaxies are merely material arms maintained by solid-body rotation in the inner disk (Kormendy & Norman 1979, RV94); indeed, given the short dynamical time scales in

the inner disk, the regular spiral structure detected in the inner 2 kpc of NGC 2403 also suggests a long-term organizing influence. However, significant spiral structure is detected only in the inner regions of these four galaxies ($r \leq 0.4 R_{25}$), in contrast to grand design galaxies such as M81 where the arms begin at $r \sim 0.2 R_{25}$ and extend to large radii.

The galaxies in this sample are relatively isolated, and there is no evidence for strong kiloparsec-scale bars; what, then, is the origin of the low-level spiral structure in these galaxies? The presence of spiral structure in isolated flocculent galaxies supports the modal theory of spiral density waves (e.g., Bertin et al. 1989a,b; Lowe et al. 1994), which suggests that spiral structure is self-excited and maintained by feedback between the stellar disk and the more dissipative, self-gravitating gas disk. Bertin et al. (1989a,b) suggest that tightly wound spiral structure is formed relatively easily in galaxies with low active disk mass, such as those with a large spheroid component. This is consistent with the observation of the most continuous spiral structure in NGC 3521 and NGC 5055, which have more significant bulges. In the context of the modal theory, low arm-interarm contrasts suggest that the conditions in the stellar and gaseous disks are not well coupled, and therefore are unable to support larger amplitude waves.

The low amplitude waves could also indicate that spiral structure in flocculent galaxies is weakly driven by another component. A slightly triaxial bulge, if rotating, could drive low-amplitude spiral structure in the inner disk; indeed, the suggestion that most galaxies have nonaxisymmetric bulges (Zaritsky & Lo 1986; Bertola, Vietri, & Zeilinger 1991) indicates that this mechanism could be generally applicable to low-level spiral structure. However, the observation of *rounder* inner isophotes suggests that a weak triaxial structure in NGC 5055 would be aligned with the minor axis, while the spiral arms appear to begin near the major axis (Figure 3d). A more detailed model of the bulge in NGC 5055 is needed to analyze its effect on disk structure. Low mass companions may provide an alternative low-level driving mechanism; indeed, NGC 5055 has two small potential companions (NGC 5023 and UGC 8313, Fisher & Tully 1981). Simulations of interactions and mergers by Byrd & Howard (1992) and Mihos & Hernquist (1994) suggest that small companions can induce spiral structure over the entire disk, which persists for as long as a few billion years. Byrd & Howard (1992) further suggest that the companion tidally perturbs the outer disk, and these perturbations in turn excite longer-lived density waves in the inner disk. However, neither simulation definitively constrains the amplitude or the extent of tidally induced spiral structure. While the ubiquity of small companions makes this mechanism attractive in explaining the origin of low-level spiral structure in seemingly isolated galaxies, further study is needed to ascertain whether it is consistent with the data presented here.

6. Summary

In this Letter, we have demonstrated the presence of low-amplitude, two-arm spiral structure in the inner disks of a sample of nearby flocculent galaxies, most notably in the prototypical flocculent galaxy NGC 5055. The observed spiral structure may be the result of self-excited spiral density waves, or the influence of a rotating, slightly triaxial bulge. Alternatively, the observed spiral structure may be driven by tidal interaction with low-mass companions; however, further study is needed to provide firmer support for this mechanism. All models discussed here suggest that regular spiral structure in NGC 2403, NGC 3521, and NGC 5055 is not particularly unique, and low-level spiral structure in flocculent galaxies could be common. The near infrared images presented here identify these galaxies as weaker counterparts to grand design spirals, and detailed studies of the ISM and star formation in future papers will help define the properties of this sample of flocculent galaxies and gauge the significance of density wave activity in different galactic environments.

Thanks to Michael Regan and Robert Gruendl for assistance with near-infrared observations. Thanks also to Christine Wilson, Lee Mundy, and Stuart Vogel for helpful discussions during the preparation of this manuscript, and to the anonymous referee for insightful suggestions. This work was supported by NSF grant AST 93-14847 and a Scholar Award from PEO International.

Table 1: Axisymmetric model fits

Galaxy	i	R_e^b	l_d^c
NGC 2403	60°	$2.5' \pm 0.6'$	$1.4' \pm 0.2$
NGC 3521	57° ^a	$0.9' \pm 0.3'$	$0.7' \pm 0.1$
NGC 4414	55° ^a	$0.1' \pm 0.3$	$0.3' \pm 0.05$
NGC 5055	48° ^a	$1.6' \pm 0.6$	$0.8' \pm 0.1$

^aDetermined from image isophotes.

^bRadius inside which half of the bulge light is found.

^cDisk scale length.

Table 2: Arm-Interarm Contrasts

Galaxy	Arm	R^a
NGC 2403	E arm	1.16 ± 0.06
	W arm	1.24 ± 0.07
NGC 3521	NE arm	1.25 ± 0.05
	SW arm	1.13 ± 0.03
NGC 4414	N “arm”	1.38 ± 0.04
	S “arm”	1.13 ± 0.03
NGC 5055 ^b	NE arm	1.29 ± 0.06
	SW arm	1.33 ± 0.06

^aDetermined from second method. See §4.3. All uncertainties are uncertainties in the mean value of R .

^b R determined from first method: 1.28 ± 0.04 for the NE arm, and 1.23 ± 0.04 for the SW arm. See §4.3.

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Fig. 1.— K' images of nearby flocculent galaxies: (a)NGC 2403, (b)NGC 3521, (c)NGC 4414, and (d)NGC 5055. Scale bar at lower right corresponds to distance along the major axis.

Fig. 2.— Plot of K' radial surface brightness profiles for NGC 4414 and NGC 5055. The crosses indicate the measured radial profile, the dashed line indicates the model disk, and the dotted line indicates the model bulge. The solid line indicates the total model distribution.

Fig. 3.— Residual K' images, after subtraction of axisymmetric bulge and disk models from the images shown in Figure 1. The scale for these images is an order of magnitude smaller than in Figure 1. White crosses mark locations of foreground stars on the face of the galaxy. (a)NGC 2403; (b)NGC 3521; (c)NGC 4414; and (d)NGC 5055. Scale bar is shown at lower right. See § 3 for details.

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